TABLE 2-2

ILLUSTRATIVE VALUES FOR THERMAL PHYSIOLOGY

Measurement	SI* Units	Traditional Heat Units
Energy equivalent of oxygen for a mixed diet	20.2 kJ/L	4.83 kcal/L
Heat of evaporation of water	2.43 kJ/g	0.58 kcal/g
For a "Typical," Healthy, Lean, Young Man:		
Mass	70 kg	
Body surface area	1.8 m^2	
Mean specific heat of the body†	3.39 kJ/(kg • °C)	0.81 kcal/(kg • °C)
Volume specific heat of blood	3.85 kJ/(L • °C)	0.92 kcal/(L • °C)
Maximum rate of O_2 consumption	3.5 L/min	
Metabolic rate at rest‡	45 W/m^2	52.3 kcal/(m^2 • h)
Core-to-skin conductance with minimal skin blood flow‡	9 W/(m^2 • °C)	10.5 kcal/(m^2 • °C • h)

*Système Internationale (in which heat is expressed in units of work)
†Calculated for a body composition of 16% bone, 10% fat, and 74% lean soft tissue (ie, nonfatty tissue, neither bone nor tooth)
‡Per square meter of body surface area
Adapted with permission from Wenger CB. The regulation of body temperature. In: Rhoades RA, Tanner GA, eds. *Medical Physiology*. Boston, Mass: Little, Brown; 1995: 611.

Heat Production

Metabolic energy is required for active transport via membrane pumps, for muscular work, and for chemical reactions such as formation of glycogen from glucose and proteins from amino acids, whose products contain more energy than the materials that entered into the reaction. Most of the energy used in these processes is transformed into heat within the body. The transformation may be almost immediate, as with energy used in active transport or with heat produced as a by-product of muscular contraction. In other processes the conversion of energy to heat is delayed, as when the energy that was used to form glycogen or protein is released as heat when glycogen is converted back into glucose, or protein back into amino acids.

Metabolic Rate and Sites of Heat Production at Rest

Metabolic rate at rest varies with body size and is approximately proportional to body surface area. In a fasting young man it is about 45 W/m^2 (Figure 2-6) (81 W or 70 kcal/h for 1.8 m^2 body surface area [Table 2-2]), corresponding to an O_2 consumption of about 240 mL/min). At rest the trunk viscera and brain account for about 70% of energy production, even though they comprise only about 36% of body mass (Table 2-3). All the heat required to maintain heat balance at comfortable environmental temperatures is supplied as a by-product of metabolic processes that serve other functions, although in the cold, supplemental heat production may be elicited to maintain heat balance.

Factors other than body size that affect metabolism at rest include gender, age, hormones, and digestion. A nonpregnant woman's metabolic rate is 5% to 10% lower than that of a man of the same age and body surface area, probably because the female

TABLE 2-3

RELATIVE MASSES AND RATES OF METABOLIC HEAT PRODUCTION OF VARIOUS BODY COMPARTMENTS

	Body Mass (%)	Heat Production (%)	
		Rest	Severe* Exercise
Brain	2	16	1
Trunk Viscera	34	56	8
Muscle and Skin	56	18	90
Other	8	10	1

*Intense or heavy
Adapted with permission from Wenger CB, Hardy JD. Temperature regulation and exposure to heat and cold. In: Lehmann JF, ed. *Therapeutic Heat and Cold*. Baltimore, Md: Williams & Wilkins; 1990: 156.

body includes a higher proportion of fat, a tissue with a low metabolic rate. (However, the growing fetus's energy requirements increase a pregnant woman's measured metabolic rate.)

Catecholamines and thyroxine are the hormones with the largest effect on metabolic rate. Catecholamines stimulate many enzyme systems, thus increasing cellular metabolism; and hypermetabolism occurs in some cases of pheochromocytoma, a secreting tumor of the adrenal medulla. Thyroxine magnifies the metabolic response to catecholamines and stimulates oxidation in the mitochondria. Hyperthyroidism may double the metabolic rate in severe cases, although an increase to 45% above normal is more typical; and metabolic rate is typically 25% below normal in hypothyroidism but may be 45% below normal with total lack of thyroxine.

Metabolic rate at rest increases after a meal as a result of the *thermic effect of food* (or "specific dynamic action," the older term). The increase varies according to the composition of the meal and the physiological state, including the level of nutrition, of the subject.[14] In a well-nourished subject the increase is typically 10% to 20%. The effect lasts several hours and appears to be associated with processing the products of digestion by the liver.

Measurement of Metabolic Rate

Heat exchange with the environment can be measured directly with a human calorimeter,[15] a specially constructed insulated chamber that allows heat to leave only in the air ventilating the chamber or, often, in water flowing through a heat exchanger in the chamber. From accurate measurements of the flow of air and water, and their temperatures as they enter and leave the chamber, we can compute the subject's heat loss by conduction, convection, and radiation; and from measurements of the moisture content of air entering and leaving the chamber, we can also determine heat loss by evaporation. *Direct calorimetry,* as this technique is called, is simple in concept but difficult and costly in practice. Therefore metabolic rate is often estimated by *indirect calorimetry*[16] based on measurements of O_2 consumption, because virtually all energy available to the body depends ultimately on reactions that consume O_2.

Consumption of 1 liter of O_2 is associated with release of 21.1 kJ (5.05 kcal) if the fuel is carbohydrate, 19.8 kJ (4.74 kcal) if the fuel is fat, and 18.6 kJ (4.46 kcal) if the fuel is protein. For metabolism of a mixed diet, an average value of 20.2 kJ (4.83 kcal) per liter of O_2 is often used (see Table 2-2). The ratio of CO_2 produced to O_2 consumed in the tissues, called the *respiratory quotient* (RQ), is 1.0 for oxidation of carbohydrate, 0.71 for oxidation of fat, and 0.80 for oxidation of protein. In a steady state in which CO_2 is exhaled at the same rate that it is produced in the tissues, RQ is equal to the respiratory exchange ratio, R; and the accuracy of indirect calorimetry can be improved by also determining R, and either estimating the amount of protein oxidized—usually small compared with fat and carbohydrate—or calculating it from urinary nitrogen excretion.

Skeletal Muscle Metabolism and Muscular Work

Even during very mild exercise the muscles are the chief source of metabolic heat, and during heavy exercise they (together with the skin) may account for up to 90% of the heat production (see Table 2-3). A healthy but sedentary young man performing moderately intense exercise may increase his metabolic rate to 600 W (in contrast to about 80 W at rest); and a trained athlete performing intense exercise, to 1400 W or more. Exercising muscles may be nearly one Centigrade degree warmer than the core because of their high metabolic rate. Blood is warmed as it perfuses these muscles, and the blood, in turn, warms the rest of the body and raises core temperature. Like engines that burn fossil fuels, muscles convert most of the energy in the fuels that they consume into heat rather than mechanical work.

When adenosine 5'-diphosphate (ADP) is phosphorylated to form adenosine 5'-triphosphate (ATP), 58% of the energy released from the fuel is converted into heat, and only about 42% is captured in the ATP that is formed. Then when ATP is hydrolyzed during a muscle contraction, some of the energy in the ATP is converted into heat rather than into mechanical work. The efficiency of this process varies enormously, and is zero in isometric contraction, in which a muscle's length does not change while it develops tension, so that the muscle does no work even though it consumes metabolic energy. Finally, some mechanical work is converted by friction into heat within the body—as, for example, happens to the mechanical work done by the heart in pumping blood. At best, no more than one quarter of the metabolic energy released during exercise is converted into mechanical work outside the body, and the remaining three quarters or more is converted into heat within the body[17] (Exhibit 2-4).

EXHIBIT 2-4

ENERGY CONSUMPTION AND HEAT PRODUCTION DURING PERFORMANCE OF MILITARY TASKS

Many military tasks require high levels of power output, and are associated with correspondingly high rates of metabolic heat production. Table 3-2 in Chapter 3, Physical Exercise in Hot Climates: Physiology, Performance, and Biomedical Issues lists metabolic rates required by men wearing the battle dress uniform (BDU) to perform 28 military occupational tasks. The added weight and stiffness of special protective clothing increase the energy cost of performing a task, and wearing the full ensemble of nuclear biological chemical protective clothing (including overgarment, boot, gloves, gas mask, and hood) over BDUs increases the rate of oxygen consumption by an average of about 10%.[1]

Of the military tasks with a high energy demand, walking and running—with or without an external load—are probably among those that are most suitable for prediction of energy requirement. For walking speeds of 2.5 km/h or greater, and light-to-moderate loads that are distributed so that their center of gravity is near the body's center of gravity, the following equation[2] predicts the metabolic power requirements for walking as a function of body weight, speed, grade, carried load, and surface:

$$M = \eta\,(W + L)\,\{2.3 + 0.32\,(V - 2.5\text{ km/h})^{1.65} + G\,[0.2 + 0.7\,(V - 2.5\text{ km/h})]\}$$

where *M* represents metabolic rate, kcal/h; η represents the terrain factor, defined as 1 for treadmill walking; *W* represents body weight in kilograms; *L* represents external load in kilograms; *V* represents walking speed in kilometers per hour; and *G* represents % grade.

Some values of the terrain factor, η, are 1.0 for blacktop surface, 1.1 for dirt road, 1.2 for light brush, 1.5 for heavy brush, 1.8 for swampy bog, and 2.1 for loose sand.[3]

Exhibit Table 1 contains some illustrative predictions for metabolic rates of a 70-kg subject walking at several speeds and grades on blacktop with no external load:

EXHIBIT TABLE 1
PREDICTED METABOLIC RATES OF A 70-KG SOLDIER WALKING AT SELECTED COMBINATIONS OF SPEED AND GRADE

	Speed			
Grade	**4 km/h (2.5 mph)**	**5 km/h (3.1 mph)**	**6 km/h (3.7 mph)**	**7 km/h (4.4 mph)**
0%	204 kcal/h	263 kcal/h	338 kcal/h	429 kcal/h
2%	379 kcal/h	536 kcal/h	709 kcal/h	898 kcal/h

Adding an external load, or substituting a less advantageous surface for blacktop, will increase the energy requirements proportionately. The cumulative effect of seemingly small changes in speed, grade, load, and terrain can impose a huge physiological burden on the body's capacity to support physical exercise and dissipate heat.

(1) Patton JF, Murphy M, Bidwell T, Mello R, Harp M. *Metabolic Cost of Military Physical Tasks in MOPP 0 and MOPP 4.* Natick, Mass: US Army Research Institute of Environmental Medicine; 1995. USARIEM Technical Report T95-9. (2) Givoni B, Goldman RF. Predicting metabolic energy cost. *J Appl Physiol.* 1971;30:429–433. (3) Soule RG, Goldman RF. Terrain coefficients for energy cost prediction. *J Appl Physiol.* 1972;32:706–708.

Heat Exchange With the Environment

Convection, radiation, and evaporation are the dominant means of heat exchange with the environment. Both the skin and the respiratory passages exchange heat with the environment by convection and evaporation, but only the skin exchanges heat by radiation. In some animal species, panting is an

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important thermoregulatory response, which can produce high rates of heat loss. In humans, however, respiration usually accounts for only a minor fraction of total heat exchange and is not predominantly under thermoregulatory control, although hyperthermic subjects may hyperventilate.

Convection is transfer of heat due to movement of a fluid, either liquid or gas. In thermal physiology the fluid is usually air or water in the environment, or blood inside the body, as discussed earlier. Fluids conduct heat in the same way as solids do, and a perfectly still fluid transfers heat only by conduction. Because air and water are not good conductors of heat, perfectly still air or water are not very effective in heat transfer. Fluids, however, are rarely perfectly still, and even nearly imperceptible movement produces enough convection to cause a large increase in the rate of heat transfer. Thus, although conduction plays a role in heat transfer by a fluid, convection so dominates the overall heat transfer that we refer to the entire process as convection. The conduction term, K, in Equation 1 is therefore restricted to heat flow between the body and other solid objects, and usually represents only a small part of the total heat exchange with the environment.

Convective heat exchange between the skin and the environment is proportional to the difference between skin and ambient air temperatures, as expressed by Equation 2:

$$C = h_c \bullet A \bullet (\overline{T}_{sk} - T_a) \qquad (2)$$

where A is the body surface area, $\overline{T}_{sk}$ and T_a are mean skin and ambient temperatures, respectively, and h_c is the convective heat transfer coefficient.

The term h_c includes the effects of all the factors besides temperature and surface area that affect convective heat exchange. For the whole body, the most important of these factors is air movement, and convective heat exchange (and thus h_c) varies approximately as the square root of the air speed (Figure 2-7) unless air movement is very slight.

Every surface emits energy as electromagnetic radiation with a power output that depends on its area, its temperature, and its emissivity (e), a number between 0 and 1 that depends on the nature of the surface and the wavelength of the radiation. (For purposes of this discussion the term "surface" has a broader meaning than usual, so that, for example, a flame and the sky are both surfaces.) The emissivity of any surface is identical to its absorptivity (ie, the fraction of incoming radiant energy that the surface absorbs rather than reflects). Such radiation, called thermal radiation, has a characteristic distribution of energy as a function of wavelength, which depends on the temperature of the surface. For a surface that is not hot enough to glow this radiation is in the infrared part of the spectrum, and at ordinary tissue and environmental temperatures virtually all of the emitted energy is at wavelengths longer than 3 microns. Most surfaces except polished metals have emissivities near 1 in this range, and thus both emit and absorb radiation at nearly the theoretical maximum efficiency. As a surface's temperature increases, however, the average wavelength of its thermal radiation decreases, and most of the energy in solar radiation is in the near infrared and visible range, for which light surfaces have lower absorptivities than dark ones.

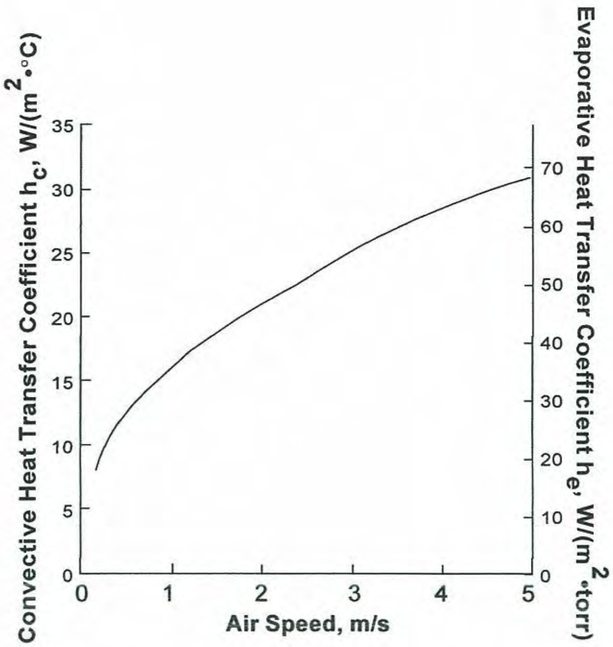

Fig. 2-7. The convective (h_c) and evaporative (h_e) heat transfer coefficients for a standing human as a function of air speed. The coefficients h_c and h_e increase with air speed in the same way, and $h_e = h_c \bullet 2.2°C/mm\ Hg$. Thus with suitable scaling of the vertical axes, as in this figure, the curves for h_c and h_e overlie each other. The horizontal axis can be converted into English units by using the relation 5 m/s = 16.4 ft/s = 11.2 mph.

If two surfaces exchange heat by thermal radiation, radiation travels in both directions; but because each surface emits radiation with an intensity that depends on its temperature, the net heat flow is from the warmer to the cooler body. Radiative heat exchange between two surfaces is, strictly, proportional to the difference between the fourth

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powers of the surfaces' absolute temperatures. However, if the difference between $\overline{T}_{sk}$ and the temperature of the radiant environment (T_r) is much smaller than the absolute temperature of the skin, R is nearly proportional to ($\overline{T}_{sk} - T_r$). Some parts of the body surface (eg, inner surfaces of the thighs and arms) exchange heat by radiation with other parts of the body surface, so that the body exchanges heat with the environment as if it had an area smaller than its actual surface area. This smaller area is called the *effective radiating surface area* (A_r), and depends on the posture, being greatest, or closest to the actual surface area, in a "spread eagle" posture, and least in someone who is curled up. Radiative heat exchange can be represented by Equation 3:

(3) $$R = h_r \bullet e_{sk} \bullet A_r \bullet (\overline{T}_{sk} - T_r)$$

where h_r is the radiant heat transfer coefficient, 6.43 W/($m^2 \bullet$ °C) at 28°C; and e_{sk} is the emissivity of the skin.

When a gram of water is converted into vapor at 30°C, it absorbs 2,425 J (0.58 kcal; see Table 2-2), the *latent heat of evaporation*, in the process. When the environment is hotter than the skin—as it usually is when the environment is warmer than 36°C—evaporation is the body's only way to lose heat, and must dissipate not only the heat produced by the body's metabolism, but also any heat gained from the environment by R and C (from Equation 1). Most water evaporated in the heat comes from sweat; but even in the cold, water diffuses through the skin and evaporates. Evaporation of this water is called *insensible perspiration*,[9,18] and occurs independently of the sweat glands. E is nearly always positive (representing loss of heat from the body); but it is negative in unusual circumstances, such as in a steam room, where water vapor condensing on the skin gives up heat to the body.

Evaporative heat loss from the skin is proportional to the difference between the water vapor pressure at the skin surface and the water vapor pressure in the ambient air. These relations are summarized in Equation 4:

(4) $$E = h_e \bullet A \bullet (P_{sk} - P_a)$$

where P_{sk} is the water vapor pressure at the skin surface, P_a is the ambient water vapor pressure, and h_e is the evaporative heat transfer coefficient.

Because water vapor, like heat, is carried away by moving air, air movement and other factors affect E and h_e in just the same way that they affect C and h_c. If the skin surface is completely wet, the water vapor pressure at the skin surface is the saturation water vapor pressure (Figure 2-8) at skin temperature, and evaporative heat loss is E_{max}, the maximum possible for the prevailing skin temperature and environmental conditions. This situation is described in Equation 5:

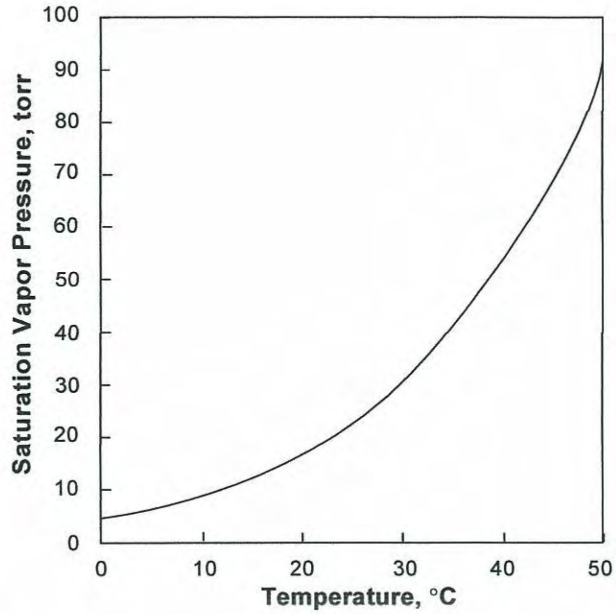

Fig. 2-8. The saturation vapor pressure of water as a function of temperature. For any given temperature, the water vapor pressure is at its saturation value when the air is "saturated" with water vapor (ie, the air holds the maximum amount possible at that temperature, or the relative humidity is 100%).

(5) $$E_{max} = h_e \bullet A \bullet (P_{sk,sat} - P_a)$$

where $P_{sk,sat}$ is the saturation water vapor pressure at skin temperature, and h_e is the evaporative heat transfer coefficient.

When the skin is not completely wet, it is impractical to measure the actual average water vapor pressure at the skin surface. Therefore a coefficient called skin *wettedness* (w)[19] is defined as the ratio E/E_{max}, with $0 \le w \le 1$. Skin wettedness depends on the hydration of the epidermis and the fraction of the skin surface that is wet. We can now rewrite Equation 4 as Equation 6:

(6) $$E = h_e \bullet A \bullet w \bullet (P_{sk,sat} - P_a)$$

Wettedness depends on the balance between secretion and evaporation of sweat. If secretion ex-

ceeds evaporation, sweat accumulates on the skin and spreads out to wet more of the space between neighboring sweat glands, thus increasing wettedness and E; and if evaporation exceeds secretion, the reverse occurs. If sweat rate exceeds E_{max}, then once wettedness becomes 1, the excess sweat drips from the body because it cannot evaporate.

Note that P_a, on which evaporation from the skin directly depends, is proportional to the actual moisture content in the air. By contrast, the more familiar quantity, relative humidity (rh), is the ratio between the actual moisture content in the air and the maximum moisture content that is possible at the temperature of the air. It is important to recognize that rh is only indirectly related to evaporation from the skin. For example, in a cold environment, P_a will be low enough that sweat can easily evaporate from the skin even if rh = 100%.

Clothing reduces heat exchange between the body and its environment through several mechanisms. By impeding air movement, clothing reduces h_c and h_e at the skin, thereby reducing heat exchange by convection and evaporation. In addition, clothing resists conduction of heat, and is at least a partial barrier to radiative heat exchange and passage of water vapor. For all of these reasons, clothing creates a microenvironment that is closer to skin temperature than is the environment outside the clothing. Furthermore, since the body is a source of water vapor, the air inside the clothing is more humid than outside. The conditions inside this microenvironment—air temperature, water vapor pressure, and temperature of the inner surface of the clothing—are what determine heat gain or heat loss by unexposed skin. These conditions in turn are determined by the conditions outside the clothing, the properties of the clothing, and the rate at which the body releases heat and moisture into this microenvironment. Therefore, the level of physical activity determines both (*a*) the appropriate level of clothing for the environmental conditions and (*b*) the degree of heat *strain* (ie, physiological change produced by a disturbance) that results from wearing clothing that is too warm for the conditions, as protective clothing often is.

Although clothing reduces heat exchange between covered skin and the environment, it has little effect on heat exchange of exposed skin. Therefore—especially when the clothing is heavy and most of the skin is covered—exposed skin may account for a fraction of the body's heat loss that far exceeds the exposed fraction of the body's surface. Thus in the cold, the head may account for half of the heat loss from the body[20]; and in someone exercising while wearing nuclear, biological, and chemical (NBC) protective clothing without gas mask and hood, donning the mask and hood while continuing to exercise may lead to a dramatic increase in heat strain.[21]

Heat Storage

Heat storage is a change in the body's heat content. The rate of heat storage is the difference between heat production/gain and heat loss (see Equation 1), and can be determined from simultaneous measurements of metabolism by indirect calorimetry and heat gain or loss by direct calorimetry. Because heat storage in the tissues changes their temperature, the amount of heat stored is the product of body mass, the body's mean specific heat, and a suitable mean body temperature (T_b). The body's mean specific heat depends on its composition, especially the proportion of fat, and is about 3.39 kJ/(kg • °C) [0.81 kcal/(kg • °C)] (see Table 2-2) for a typical body composition of 16% bone, 10% fat, and 74% lean soft tissue (ie, tissue that is neither bone nor tooth, and is not fatty). Empirical relations of T_b to core temperature (T_c) and $\overline{T}_{sk}$, determined in calorimetric studies, depend on ambient temperature, with T_b varying from $0.67 \bullet T_c + 0.33 \bullet \overline{T}_{sk}$ in the cold to $0.9 \bullet T_c + 0.1 \bullet \overline{T}_{sk}$ in the heat.[19] The shift from cold to heat in the relative weighting of T_c and $\overline{T}_{sk}$ reflects the accompanying change in the thickness of the shell (see Figure 2-2).

HEAT DISSIPATION

Figure 2-9 shows rectal and mean skin temperatures, heat losses, and calculated shell conductances for nude resting men and women at the end of 2-hour exposures in a calorimeter to ambient temperatures from 23°C to 36°C. Shell conductance represents the sum of heat transfer by two parallel modes (ie, conduction through the tissues of the shell, and convection by the blood); it is calculated by dividing heat loss through the skin (HF_{sk})—(ie, total heat loss less heat loss through the respiratory tract)—by the difference between core and mean skin temperatures, as shown in Equation 7:

$$C = HF_{sk} / (T_c - \overline{T}_{sk}) \qquad (7)$$

where *C* is shell conductance, and T_c and $\overline{T}_{sk}$ are core